

11/17/95 JS

October 1995 • NREL/TP-411-20016

PV Cz Silicon Manufacturing Technology Improvements

**Final Subcontract Report
1 April 1992 – 31 May 1995**

T. Jester
Siemens Solar Industries
Camarillo, California



National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. DE-AC36-83CH10093

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PV Cz Silicon Manufacturing Technology Improvements

Final Subcontract Report 1 April 1992 – 31 May 1995

T. Jester
Siemens Solar Industries
Camarillo, California

NREL technical monitor: R. Mitchell



National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Subcontract No. ZM-2-11040-1

October 1995

MASTER

jm
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This publication was reproduced from the best available camera-ready copy submitted by the subcontractor and received no editorial review at NREL.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (615) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650



PREFACE

Siemens Solar Industries (SSI) began a three-year, three-phase cost shared contract in March 1992 to demonstrate significant cost reductions and improvements in manufacturing technology. The work has focused on near-term projects for implementation in the SSI Czochralski (Cz) manufacturing facility in Camarillo, California.

The work has been undertaken to increase the commercial viability and volume of photovoltaic manufacturing by evaluating the most significant cost categories and then lowering the cost of each item through experimentation, materials refinement, and better industrial engineering.

Significant contributions have been made by the key personnel involved in the program. They include Jerry Anderson in module and cell evaluations, Kim Mitchell, David Tanner and Karen Pauls in the crystal growth and wafer areas, Rob Probst in the cell area, and Sergio Vasquez in the environmental, safety and health area.

SUMMARY

OBJECTIVES

The objective of the program is to reduce costs in photovoltaic manufacturing by approximately 10% per year. The specific milestones are shown in Table 1. The program consists of three focused tasks relating to cost reduction. The silicon wafer itself contributes about half of the total cost and has the most potential for cost reduction. The cell processing costs are about a quarter of the total costs, with cell efficiency results being most important. Module assembly and packaging costs are the balance, with the module design, both materials and labor, contributing significantly.

Table 1. Cz manufacturing technology milestones.

	Phase 1	Phase 2	Phase 3
Task 1. Silicon Crystal Growth & Thin Wafer Technology			
A. Increase Cz grower productivity by 25%	10%	15%	25%
B. Demonstrate utility of prototype wire saw Deliver 100 wire sawn wafers	• •		
C. Demonstrate 0.010"-thick wire sawn wafers Deliver 100 0.010" wafers		• •	
D. Reduce wafer cost by 30%		15%	30%
Task 2. Silicon Cell Processing Reduce cell cost by 30% (\$/watt)	10%	20%	30%
Task 3. Silicon Module Fabrication & Environmental, Safety & Health Issues			
A. Reduce module fabrication costs by 35% Deliver modules demonstrating reduced \$/watt	10%	25% 2 modules (20%)	35% 6 modules (25%)
B. Reduce caustic use and waste	Define process and equipment	10% reduction	35% reduction
C. Replace CFC's	Evaluate CFC alternatives		90% reduction in CFC usage

Task 1: Silicon Crystal Growth and Thin Wafer Technology. Crystal growing costs are driven by material growing yields and indirect manufacturing costs such as electricity and machine parts used each time a crystal ingot is fabricated. Wafering costs are driven by labor and the number of good slices yielded per length of crystal processed. This first task of reducing the wafer costs has focused on the graphite and crucible usage in the crystal growing machines, the polysilicon material used for ingot growth, increasing ingot size and the evaluation and implementation of wire saw machines to improve the yielded wafers per inch of ingot.

Task 2: Silicon Cell Processing. Cell processing costs are driven by the electrical contacts used, and the labor required for the process steps to clean the wafer, form the semiconductor junction, and the contacts. The second task has been focused on the improvement of the etching bath process for better uniformity, better junction formation, and reduced contact resistance. Fabrication of larger cells has also had a significant cost impact. Improvements in process automation for lower labor costs have been implemented.

Task 3: Silicon Module Fabrication and Environmental, Safety, and Health Issues. Module costs are highly sensitive to labor and materials. The module design tasks are driven by high reliability in the field and lower costs. Module cost reductions have been done by development and production of larger modules and development of lower cost components. Included in this task is the environmental work to eliminate chlorofluorocarbon (CFC) usage and significantly reduce the caustic waste volumes.

DISCUSSION AND CONCLUSIONS

During this program, several significant manufacturing technology improvements were achieved.

The crystal growing operation improved significantly with a complete redesign of the graphite hot zone parts. This redesign improved the lifetime of these expensive machine parts by more than a factor of three and has resulted in a savings of over \$300,000 annually. This design effort is complete and all the crystal growers at SSI have been retro-fitted to include these parts. Crystal growing improvements were also achieved by an on-going study of the polysilicon materials used versus crystal yield. A three-month study of various polysilicon remelt runs versus runs with virgin polysilicon chips mixed in was conducted. Higher resistivity polysilicon remelt alone shows much higher growing yields, which is believed to be due to the higher state of refinement. This benefit is two-fold, with remelt polysilicon typically much less expensive than the virgin material.

Larger charge sizes with larger crucibles have been implemented for a productivity gain as well as larger diameter ingot growth. Both items have had large cost reduction impact.

Productivity in the crystal growth process increased by over 25% in one year alone under this program.

Wafer processing with wire saws progressed rapidly. The wire saws have proven to yield 50% more wafers per inch in production. The capacity of a wire saw is much greater than that of an ID saw, resulting in major labor savings for a given manufacturing throughput. The major trade-off with wire saws is an increase in the cost of the slurry cutting media. Full conversion from ID saws to wire saws has been realized in the manufacturing process.

Cell processing improvements have included the implementation of a new etching process with better uniformity across the wafer surface, and process variations in junction formation and optics, including improvement in cell and module performance. A significant result during this study was the quantification of the sensitivity of certain diffusion processes to humidity exposure. This finding led to implementation of an additional etch step for thorough cleaning of the cell surface prior to contact firing. Improved electrical performance of the complete production volume has been achieved with additional efforts on contact paste studies. Automation of a large portion of the cell line has been implemented.

Module designs for lower material and labor costs have been implemented with the focus on a new junction box and less costly framing technique. A larger 75W modules has been designed, developed and implemented in commercial production under this contract. CFC usage has been eliminated in the SSI manufacturing facility under this contract. Studies of methods to reduce caustic and fluoride waste have been done, and cost reduction of over 65% for caustic waste has been realized.

Table 2 shows the categories and total savings for manufacturing cost improvement as completed under this contract. As can be seen, the 30% overall goal has been met. In addition, the complete elimination of CFC use exceeded the contract goals by over two years.

Table 2. Summary Cost Reduction

<i>Category</i>	<i>% Reduction in Cost</i>
1. Crystal Growth/Thin Wafers - Large crucible - 43 vs. 29 wafers/inch - Large ingot	13%
2. Cell Improvements - 4% electrical improvement - Large Cell	5%
3. Module Improvements - Automated Assembly - Large Module - New J-Box	12%
Total	30%

SECTION 1.0

CRYSTAL GROWTH AND THIN WAFER TECHNOLOGY

The Crystal Growing Operation in Camarillo increased throughput by over 25% during this contract. The increase is attributable to several factors including improved poly quality and cleaning, upgrades to the growing equipment, specifically diameter controls, and upgrades to the hotzone parts which have increased reliability and reduced cycle time. Larger diameter ingots and larger crucibles have contributed over 8% to this improvement.

1.1 Polysilicon Study:

A wide range of poly silicon starting materials have been evaluated. Crystal Growing yields, cell performance and impurity analysis have been conducted. Overall crystal growing yields improved by 4% as a result of the study.

1000 kg of Semi-Prime virgin poly material was purchased and run through the normal crystal growing process. In Figure 1-1. the yields for the 30 experimental crystal growth runs are compared to the baseline process. Though the Semi-Prime material improved yields, the yield improvement observed was not able to justify the added cost of the Semi-Prime virgin material.

Remelt from outside sources was investigated. As shown in Figure 1-2., the resistivity of the starting material plays a role in the quality of the grown ingot and has a direct affect on the crystal growing yield. Through this study it was determined that 1-3 Ohm-cm, n-type material consistently produced the lowest crystal growing yields. This material must be heavily counter doped in order to grow 1-2 Ohm p-type material. In comparison, remelt material which is >10 Ohm-cm, n or p-type, repeatedly produces the highest yields for remelt material purchased from outside vendors.

SSI uses inhouse remelt material as feed stock for ingot growth. Inhouse remelt used includes tops, tails, slabs and selected plugs, those which are not suspected of containing quartz chips or other foreign material. Historically, the yields obtained using the slab material were low, believed caused by the heavy oxide buildup on the sides of the ingot. During 1991, use of slab material was stopped until a cost effective method of cleaning the slabs could be found.

Using an abrasive tumbler we were able to abrade off the outside layer of the slab material, increasing the crystal growing yields. Further studies, summarized in Figure 1-3., were conducted which showed that an overall yield improvement was obtained by placing all remelt material, inhouse and vendor material, through the tumbling process. Yields may still be improved by decreasing the material lost in this process.

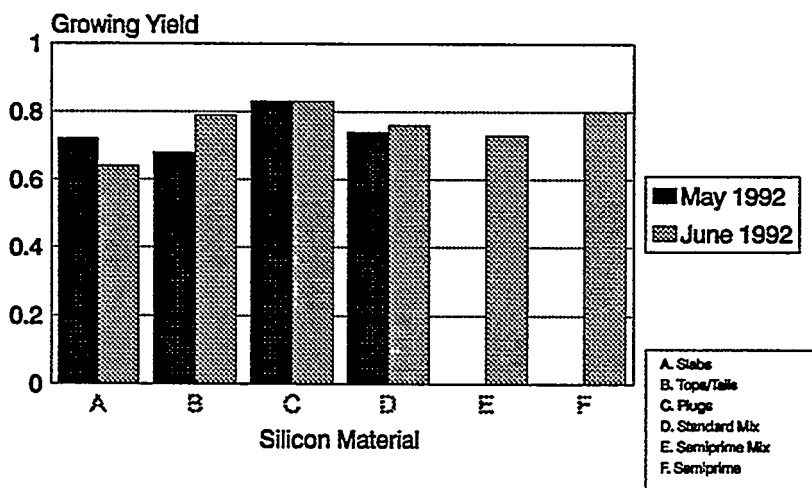


Fig. 1-1. Semi-Prime Poly Silicon Study

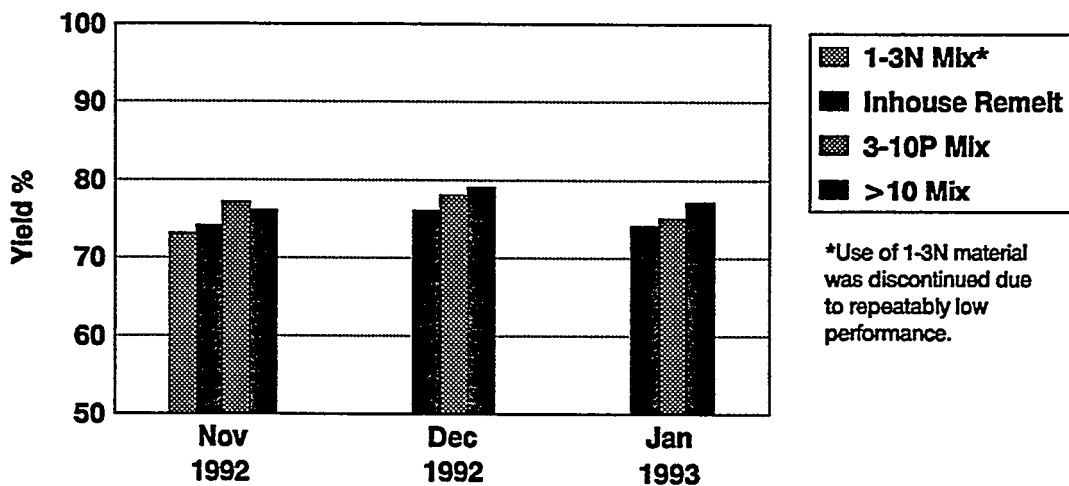


Fig. 1-2. Resistivity Effects of Poly Silicon on Growth Yields

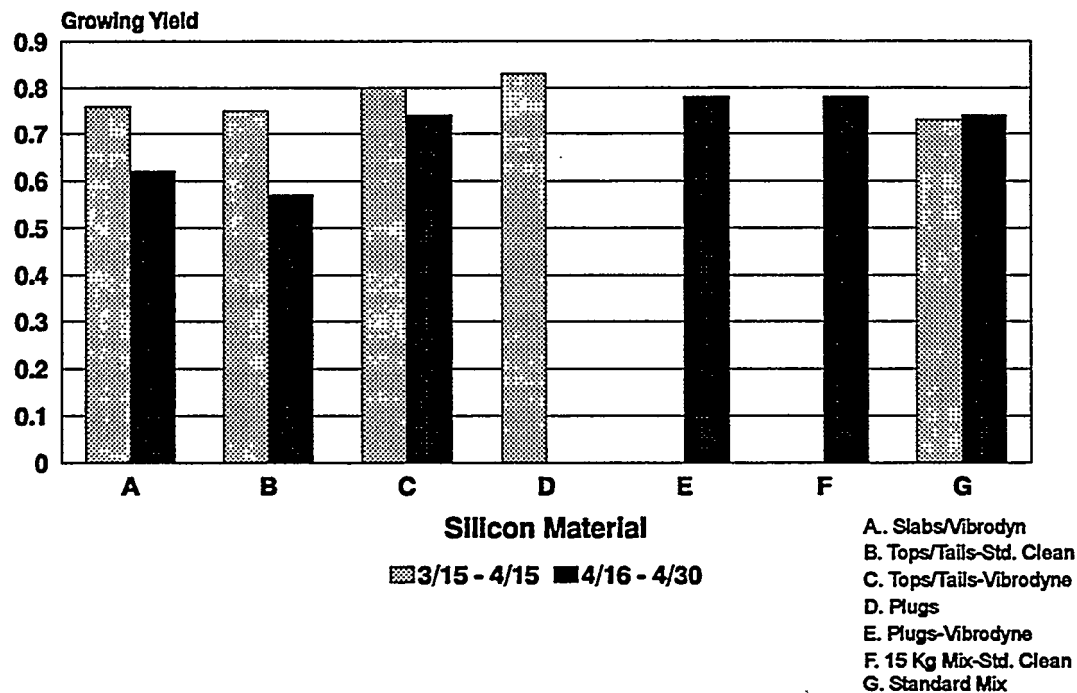
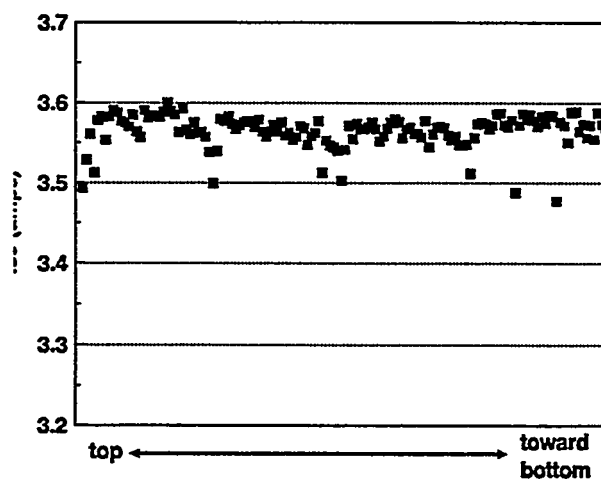


Fig. 1-3. Effect of material cleaning on crystal growth yield.

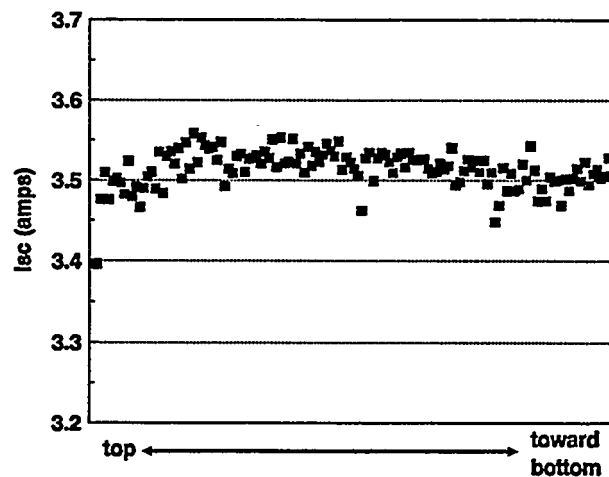
1.2 Crystal Growth:

Experimentation with crystal growth techniques began during the first phase of the contract.

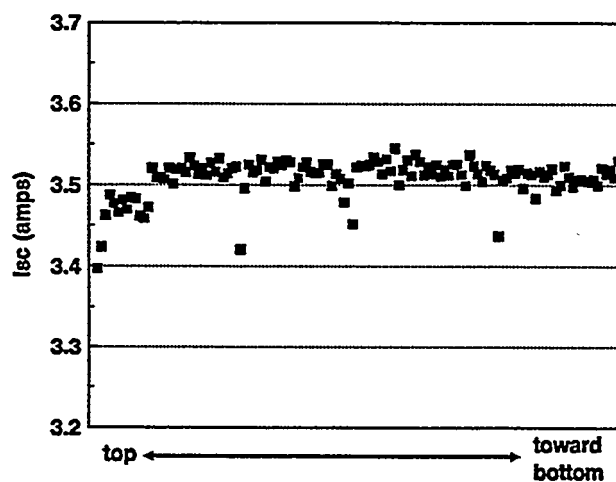
Experiments initially focused on better techniques for growing ingots from this material. Two types of necking were tested: "step" necking, which produces the fewest dislocations but is slower, and "paintbrush" necking, which is faster and easier from an operations standpoint. The concern during faster pull speed necking is the creation of "slip" dislocations in the crystal structure. The electrical effect of slip dislocation has shown to reduce short circuit current in processed cells. This has been reported by K. Pauls [1]. Cells made from these two different types of ingots do not show a significant difference in electrical performance, thus the faster technique is desirable for production throughput considerations. The results are shown in Figure 1-4.



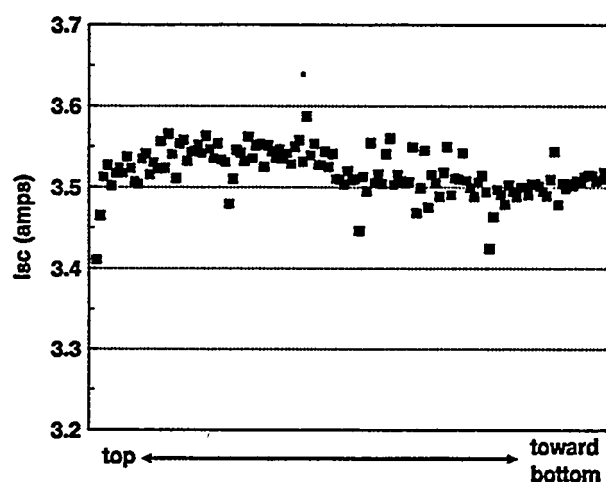
a. step necking.



b. step necking.



c. paintbrush necking.



d. paintbrush necking.

Fig. 1-4. Crystal Growth Technique Study

1.3 Hotzone:

In 1989 SSI installed crystal growers in Vancouver, WA. The hot zone installed in these growers included designs similar to those common throughout the industry. The growers in Camarillo continued to run with an older hotzone design, partially due to the difficulty of adapting the Vancouver design to the shorter tanks found on the older, Camarillo growers. The lifetime of several of the key graphite parts used on the older growers was considerably lower than was possible with a better design.

In the spring of 1992 work began on the design of a new hotzone for the Camarillo crystal growers. The design was tested and eventually implemented on all growers. The results have been remarkable. The most leveraging change was to be able to use the Vancouver style graphite susceptor, which holds the crucible during the run. Several other design changes were required to allow the Vancouver susceptor to be used in Camarillo.

The old graphite susceptor had a top and bottom piece and was used for 4-6 runs before being replaced. The new susceptor design as shown in Figure 1-5, costs slightly less per unit than the old design, and is used for 18-22 runs. The savings in direct materials cost for the susceptor alone is \$224,000. Other savings resulting from design improvements include the heaters and insulating heatpack. The total yearly cost savings for the project was confirmed at over \$300,000 during phase II and III of the contract.

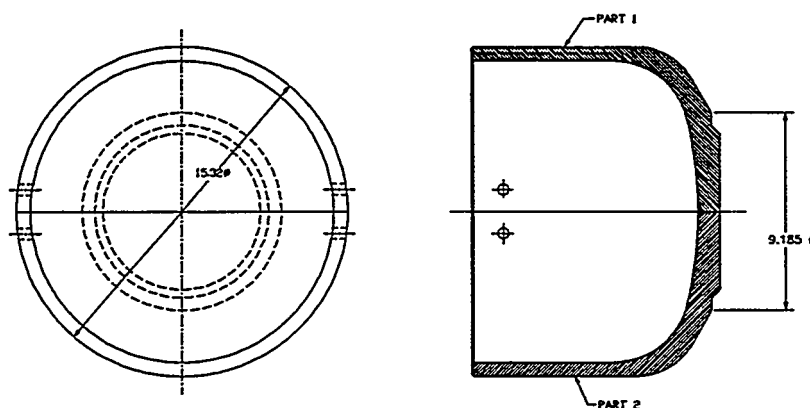


Fig. 1-5. Crystal Growth Graphite Susceptor Design.

1.4 Larger Diameter Ingots:

A significant cost reduction in the total module cost is realized by making larger modules, with larger cells.

Larger diameter ingots have been grown in order to increase cell size by 35%. A slightly larger diameter ingot of nominal 5.5" is being grown which has resulted in a 6% increase in ingot cross sectional area. This 6% ingot cross section area increase is a direct improvement in production volume, for no additional cost. A diagram of the new larger ingot is shown in Figure 1-6. This change also included a new ingot shape to maximize the area of the cell from the grown ingot. An analysis of the subsequent processes in the production facility showed that a small flat area is required for machines which align mechanically to the wafer. With the diameter tolerance on as grown ingot being considered, the shape shown in Figure 1-6. with 125 mm flats was designed. This new ingot produces a cell with 35% more active area with reference to the standard 4.05" square cell. This change in production posed no significant problems.

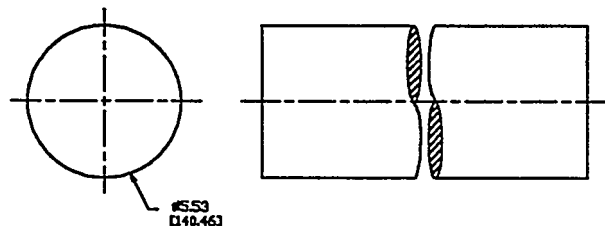


FIG 1
125 MM INGOT

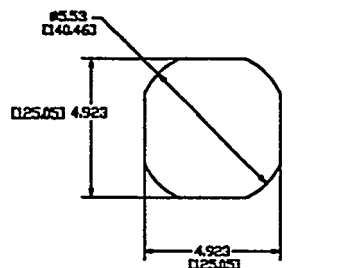


FIG 2
125 MM WAFER

Fig. 1-6. Larger Diameter Ingot

1.5 Recharge:

Most of the effort in Vancouver for 1992 was concentrated on the investigation and development of a recharge process. The process chosen was batch recharge as opposed to semi-continuous recharge. The process was never able to obtain the yields required to compete with the baseline process. Figure 1-7. shows the yields for the recharge process as compared with the baseline process for the months of March through August. The low yield for the recharge process is a result of the poor quality of recharge poly material. The prohibitive cost of better material far outweighs the cost savings of the crucible usage for recharge. At this time, SSI has decided against further development of a recharge process.

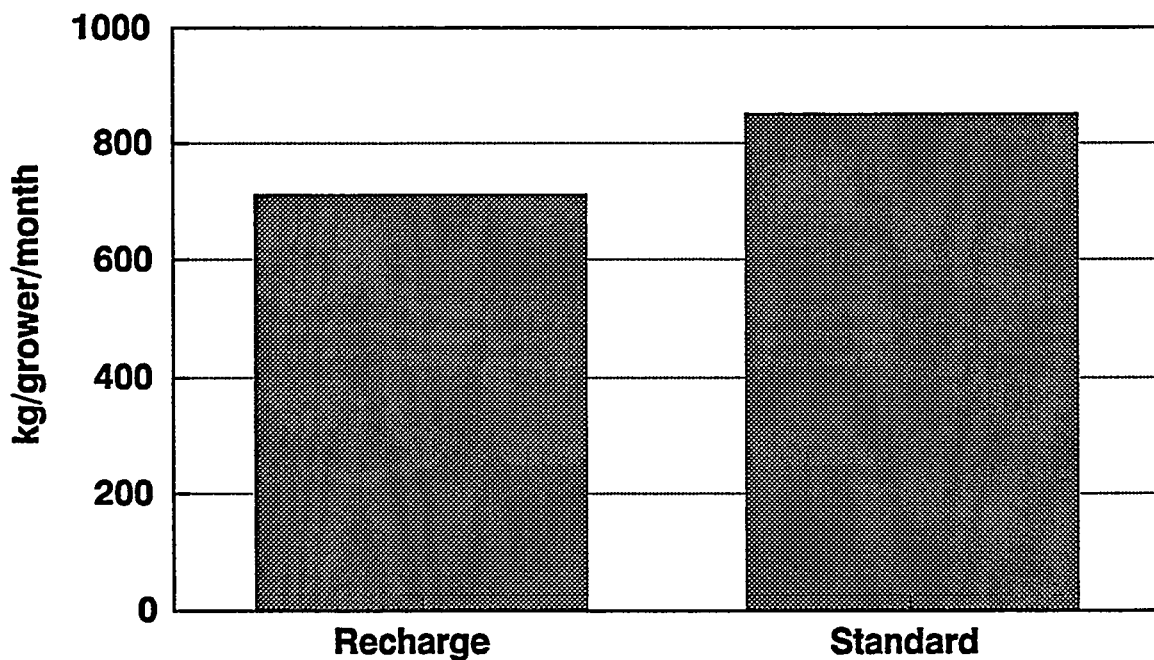


Fig. 1-7. Recharge Process v. Standard Growth Process

1.6 Crucible Studies:

A two part study of oxygen concentration was begun during this phase. The study includes looking at different types of crucibles and altering growth parameters like pull speed and rotation speed.

The crucible is the major source of the oxygen which is incorporated into a silicon ingot during growth. Crucibles with a denser, bubble free layer on the inside wall have been shown to devitrify less and to contribute less oxygen to the melt. A set of "low bubble" crucibles was compared to standard crucibles and samples of the silicon ingot taken from the top and the bottom of the ingots. Fourier Transform Infrared, FTIR, technique was used to measure the oxygen concentration on each sample. The results, Figure 1-8., show the oxygen concentration for the low bubble crucible to be lower at the bottom of the ingot than for the standard crucible.

Additional focus on throughput has initiated the use of larger diameter crucibles in the existing crystal growers. Initial pilot runs were conducted with no disruption to the production process, and with comparable growth yields. The larger crucibles have demonstrated over 10% improvement in kg/day grown, with virtually no cost addition. This improvement has been implemented in 80% of the production growers to date.

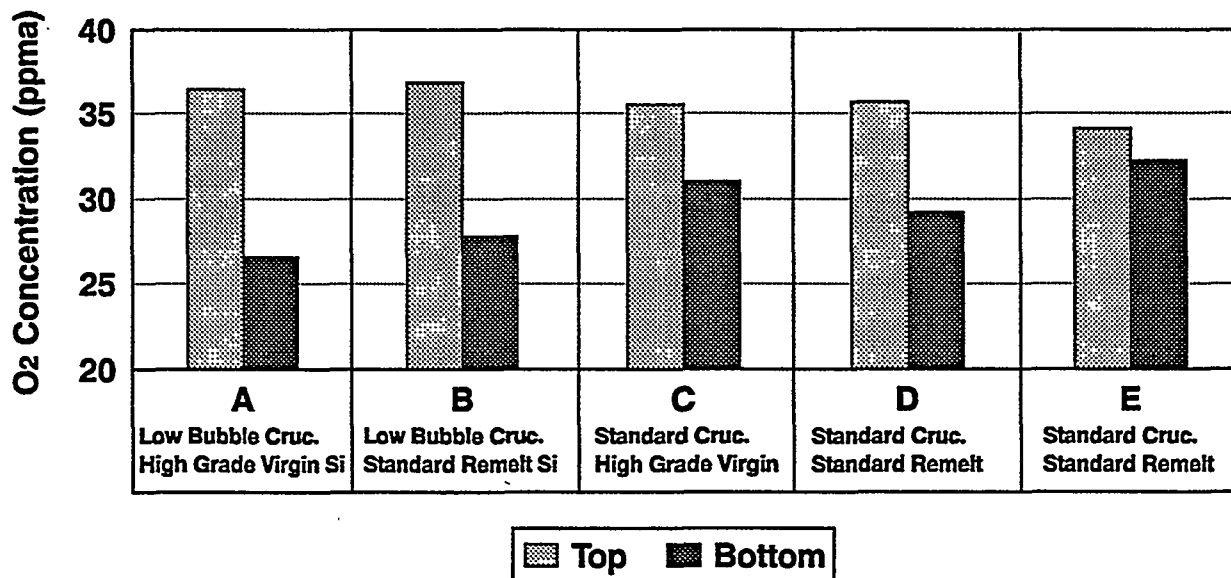


Fig. 1-8. Crucible Study

1.7 Wiresaw Evaluation:

A prototype, commercially available wiresaw was tested and a process developed for manufacturing of silicon wafers for photovoltaic use.

Wiresaw process improvements completed during this program include improved slurry mixing, implementation of a spray wash at the conclusion of a wiresaw run, installation of slurry manifolds to uniformly distribute slurry, and implementation of vacuum chuck mounting of the ingots which significantly reduced set-up time.

The most significant of these control parameters has been the combination of wire usage and slurry usage. The yield trend with number of slurry runs is shown in Figure 1-9. The quality of wafers sliced varies significantly in thickness control and taper (non-parallel sides) if these parameters are not tightly controlled. The goal is to maximize the amount of runs obtained with each wire change and slurry batch used. The amount of these materials consumed per run or per wafer is a very important parameter for cost effectiveness in manufacturing high volumes of wafers.

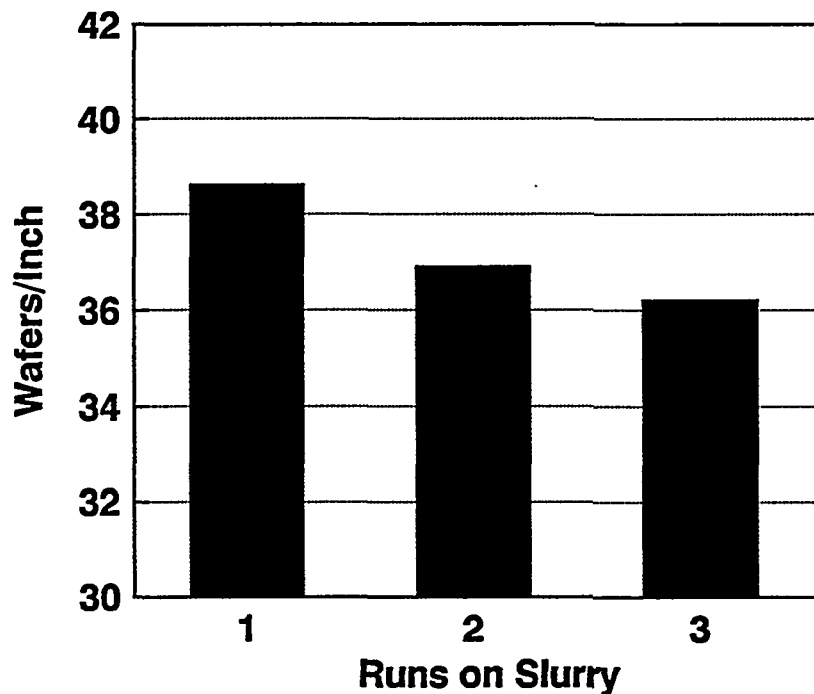


Figure 1-9. Yielded wafers per inch v. slurry use.

1.8 Wire Saw Implementation:

Wire saw implementation was the focus for wafer fabrication during this phase of the contract. Complete conversion from Inner Diameter (ID) saws to wire saws was accomplished during this phase .

Wafer yield per inch has improved substantially with this change over. In addition to less material lost with each slice, the ability to slice thinner wafers has had a substantial impact. Wafer thickness has decreased by 40% with wire saws; from .021" thick as sliced with ID saws to .013" thick with wire saws. Wafer yield has improved from 29 wafers per inch of ingot with ID saws to over 44 wafers per inch with wire saws, resulting in a greater than 50% increase in capacity. Figure 1-10. shows this improvement in yielded wafers per inch.

Slicing the larger diameter ingot discussed in section 2.4 posed no significant issues for wire sawing.

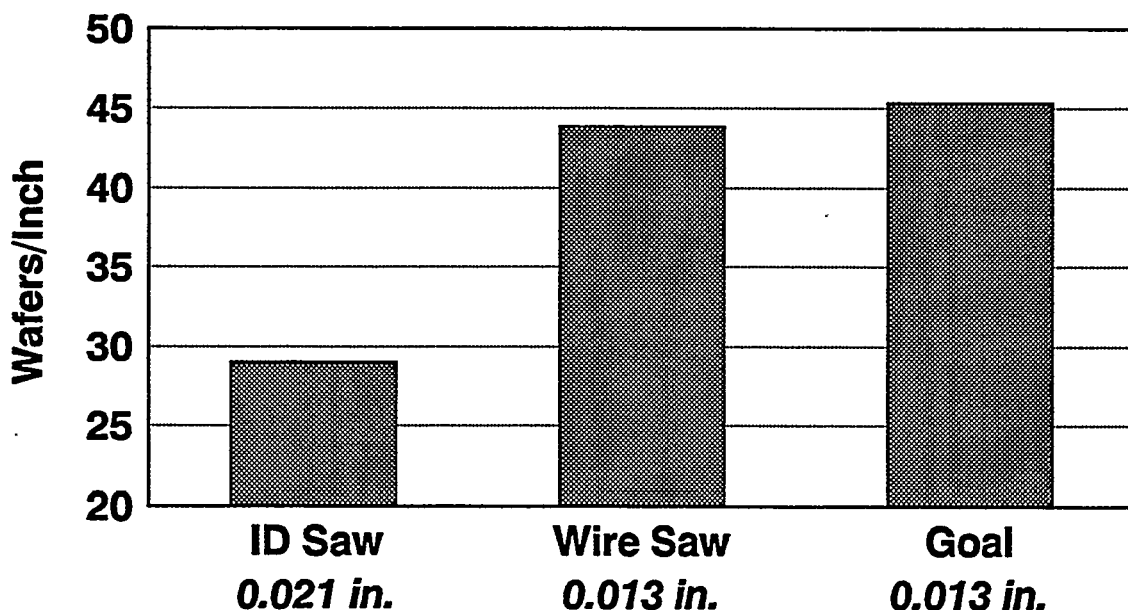


Fig. 1-10. Yielded wafers per inch, ID saws v. Wire Saws.

1.9 Wire Saw Yield:

Wire saw mechanical yields, showed large improvements during the last two phases of the contract. Yield values in Figure 1-11., show the mechanical improvement seen over the last year, with significant events noted on the chart. The major improvement to move from 80% yield to 90% was a result of the improvement in material quality characteristics of the oil and the wire. The wire must be defect free, and the oil viscosity must be tightly controlled, to achieve greater than 90% mechanical yield.

Wire saw mechanical yields also improved by attention to training of the operations personnel. With multiple wire saws operating round the clock, operator interaction with the machine is a critical parameter to be focused on.

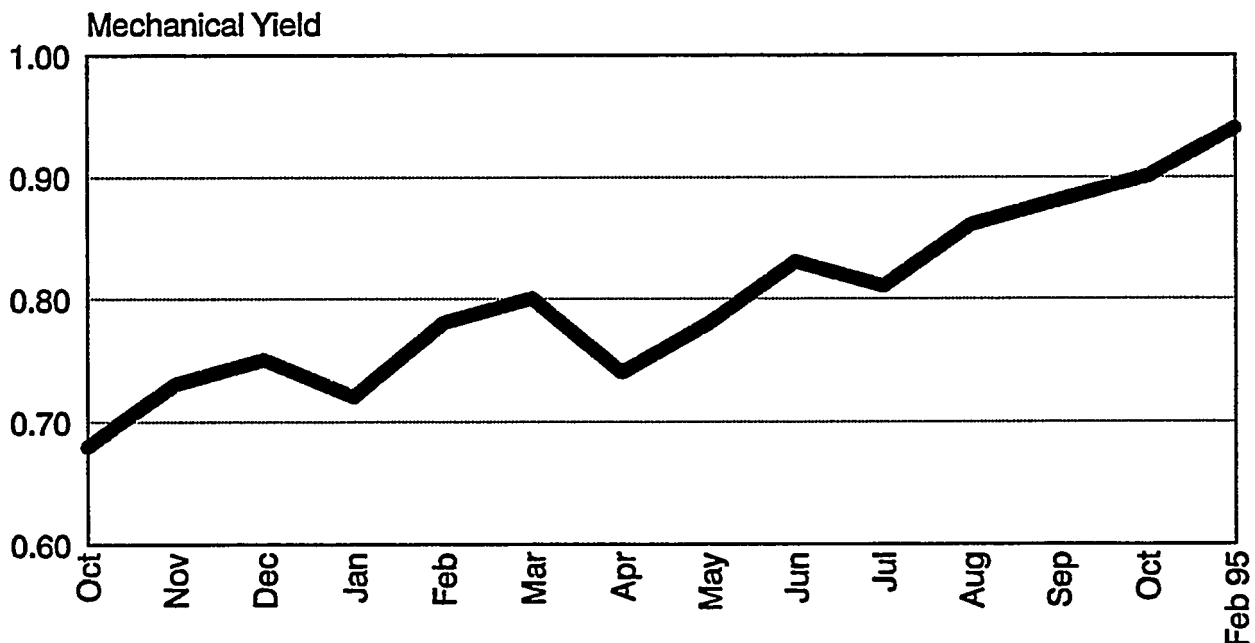


Fig. 1-11. Wire Saw Yield Improvement

1.10 Thin wafers:

During Phase I of the project, the wafer thickness was reduced from 450 microns to 330 microns. The thickness reduction was possible because of the reduction in surface damage using the wiresaw, compared with the damage caused by ID saws which then needs to be removed. The yield and electrical performance data of this change is discussed in the following section. All thin wafer deliverables were met under this contract. Figure 1-12. shows a typical thickness distribution produced in the wire saw process.

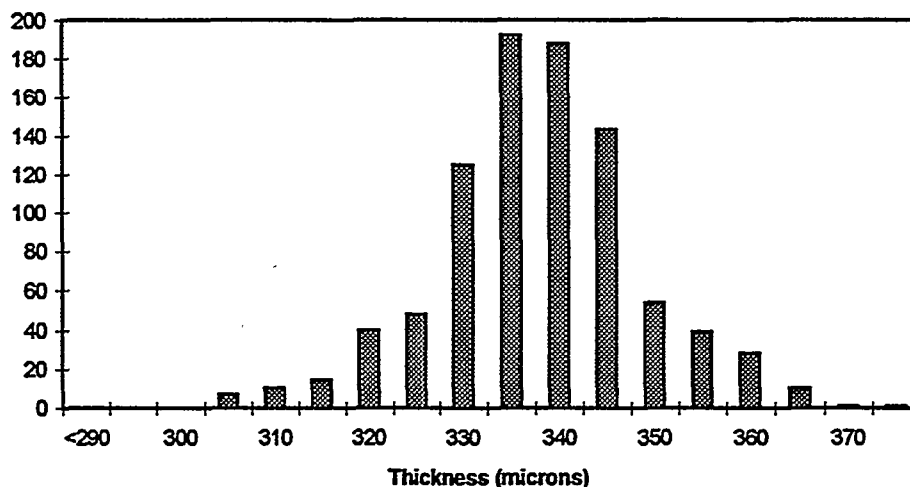


Fig. 1-12. Thickness variation from wire saw process.

SECTION 2.0 CELL PROCESSING

Cell processing costs are driven by the amount of silicon used per cell (wafer thickness), the electrical performance of the cells, and the labor required for the processing of wafers into active cell devices. The work in this area has been focused on the reduction of labor through automation of various steps, the improvement of the electrical means of the cells processed by improving the contact resistance and diffusion processes. This work has been overlaid onto the results incurred by using thinner wafers. Yields and performance v. cell thickness have been closely monitored, and are described below.

As cell thickness has decreased, the need for automated handling has increased. This coupled with the necessary reduction in labor costs, required a whole new method for anti-reflective coating, printing and firing, and testing cells.

2.1 Thin Cells:

A study done to examine the effect of wafer thickness, mechanical yield, and electrical performance was performed during the second quarter of this contract. The experiment used four groups of wafers, two cut by both ID and wire saws. The experimental groups, and the test results are shown below:

Experimental Groups

1. "A" wafers, 17.5 mil cut by ID saws
 2. "B" wafers, 17.5 mil cut by wire saws
 3. "C" wafers, 21 mil cut by ID saws
 4. "D" wafers, 15 mil cut by wire saws
- All groups were run through the standard production line with no special handling.
 - Groups "A" and "D" were etched to 14 mils at the wetline.
 - Groups "B" and "C" were etched to 17 mils at the wetline

Table 2-1. Cell and Wafer Thickness v. Performance

Groups-->	A	B	C	D
Total wafers processed	7560	5740	7000	8960
Total cells completed	7054	5573	6787	8217
% loss (Breakage)	6.69	2.91	3.04	8.29
AMP (mean)	3.19	3.24	3.20	3.20
Loss at soldering (%)	1.7	3.9	1.7	1.5
Average module (Watts)	53.46	53.81	54.13	54.32
Standard Deviation	0.63	0.45	0.67	0.44

The results of the tests can be summarized as follows:

- Breakage was highest with the thin wafers, especially the thin wire saw wafers. This result had been expected. Most of this breakage did occur at print, dry, fire operations because of the multiple handling steps, followed by the diffusion area which also has a boat transfer operation. The thicker ID and wire sawn wafers did not show a significant difference in breakage and the "thin" ID and "thin" wire indicated a comparable breakage.
- The Electrical mean_(amps) did not show significant differences.
- Automation or semi-automation of wafer handling between the AR coater, printers, and testing machines needed to be implemented.

2.2 Cell Electrical Performance:

The cell electrical distribution has improved significantly as a result of improved contact and diffusion processes. In defining and experimentation with process changes, an interesting and significant cell performance sensitivity was discovered. Certain processes showed sensitivity to environmental exposure, particularly humidity exposure. Figure 2-1. shows the results of humidity exposure v. process type with a significant change in the amount of Phosphorus present before and after exposure. This larger amount of Phosphorus coincided with visible delaminations in the modules made with these cells.

Through these studies, coupled with contact firing process changes, contact coverage re-design and diffusion changes, a significant shift in the electrical performance was effected. This shift is shown in Figure 2-2. It should be noted that this effort also reduced the amount of Silver paste used for the front contact by over 48%. This savings in materials represents an annual savings of over \$100,000 in material usage.

The development work done under the Cell Processing Task of this contract has yielded greater than a 5% improvement in cell costs.

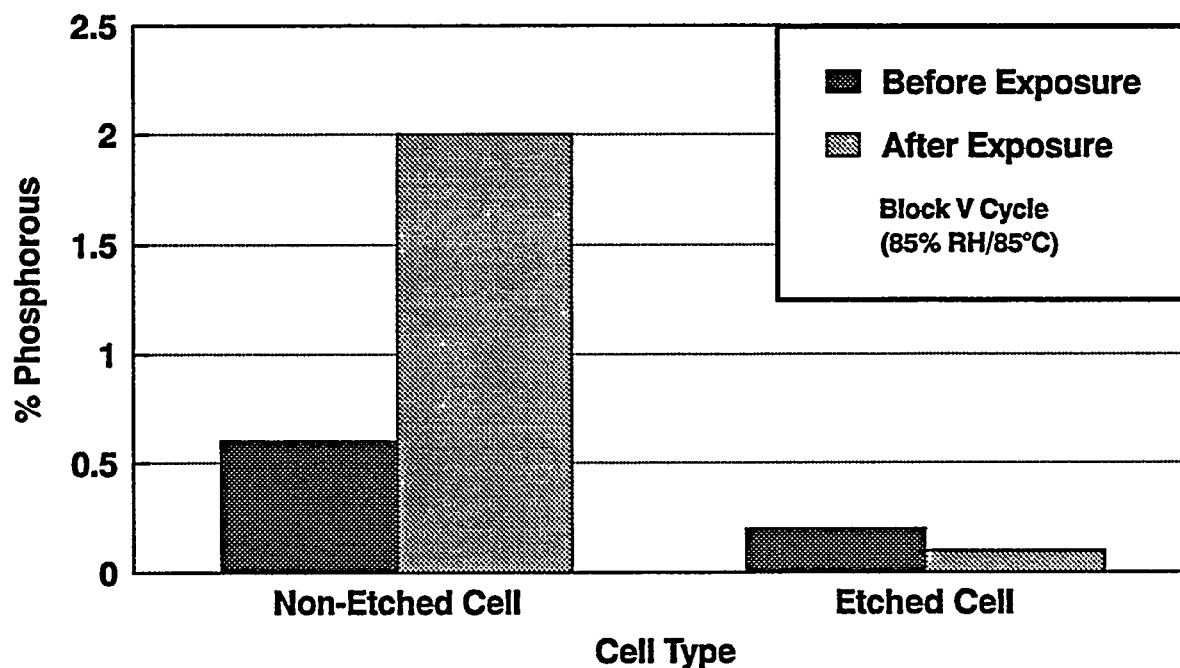


Fig. 2-1. Humidity Sensitivity Study
Eight Days Humidity Freeze Cycle

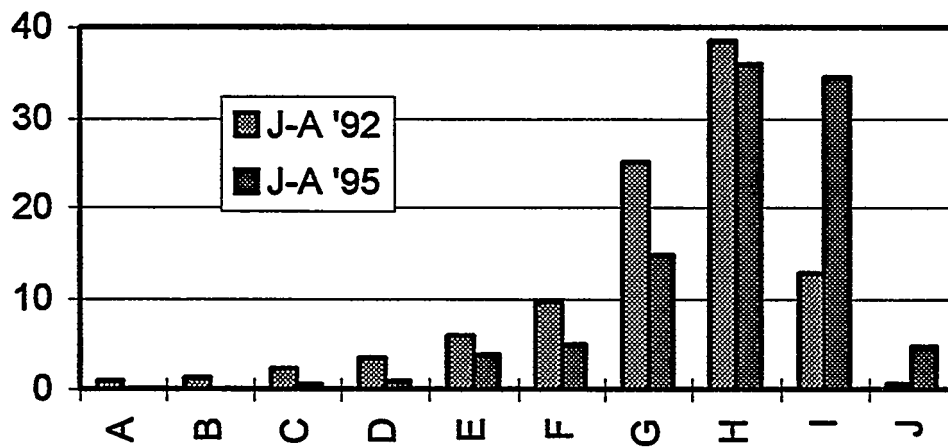
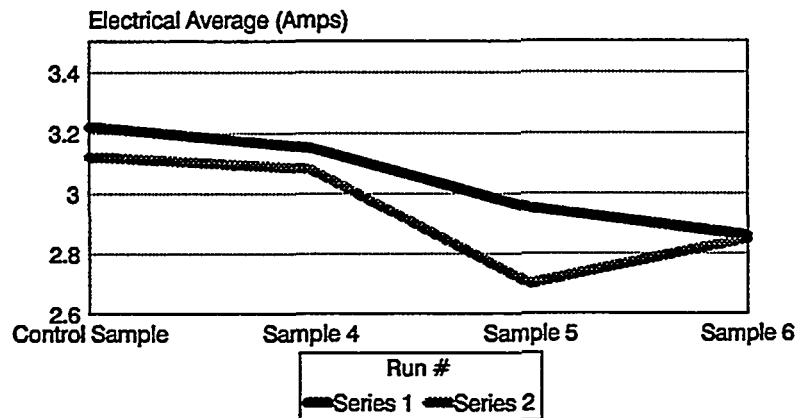


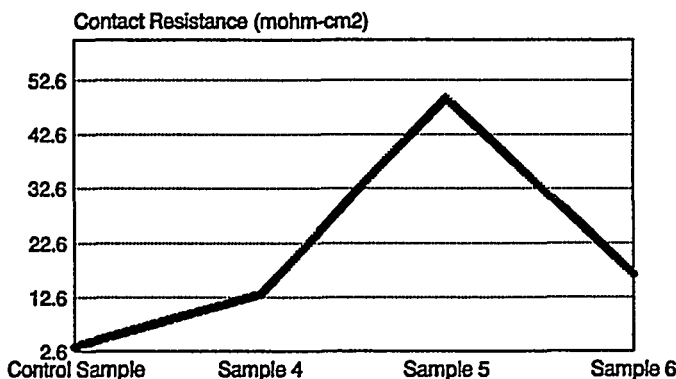
Fig. 2-2. Summary Electrical Improvement

2.3 Contact Paste Studies:

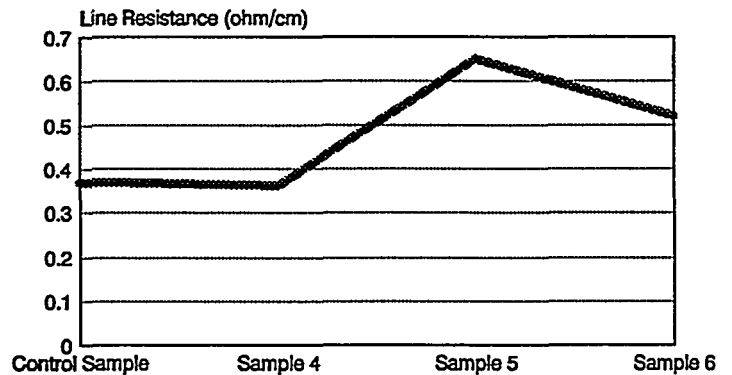
A paste study conducted with Ferro Corporation to improve the electrical contacting of cells was performed in which the standard paste formulation was modified in an effort to reduce both the contact resistance to the cell and the linear resistance of the grid lines. The standard paste used in production continues to be the best performer in all categories of electrical amps produced and lowest contact and line resistances. Figure 2-3. (a-c) shows the contact paste comparison study results.



a. Electrical performance of cells with various pastes



b. Contact resistance



c. Line resistance

Fig. 2-3. Contact paste comparison study

2.4 Automated Cell Processing:

Automated handling systems have been designed and installed in the cell fabrication area during this phase of the contract. The result has been the reduction of over 50% of the labor required in this portion of the cell process. The automated handling system begins with the anti-reflective coating process and ends with a tested cell. The transfer points are a combination robot, and pick and place mechanism system. A flowchart of the process is shown in Figure 2-4. in which the solar cells are automatically machine handled throughout this area of the production facility.

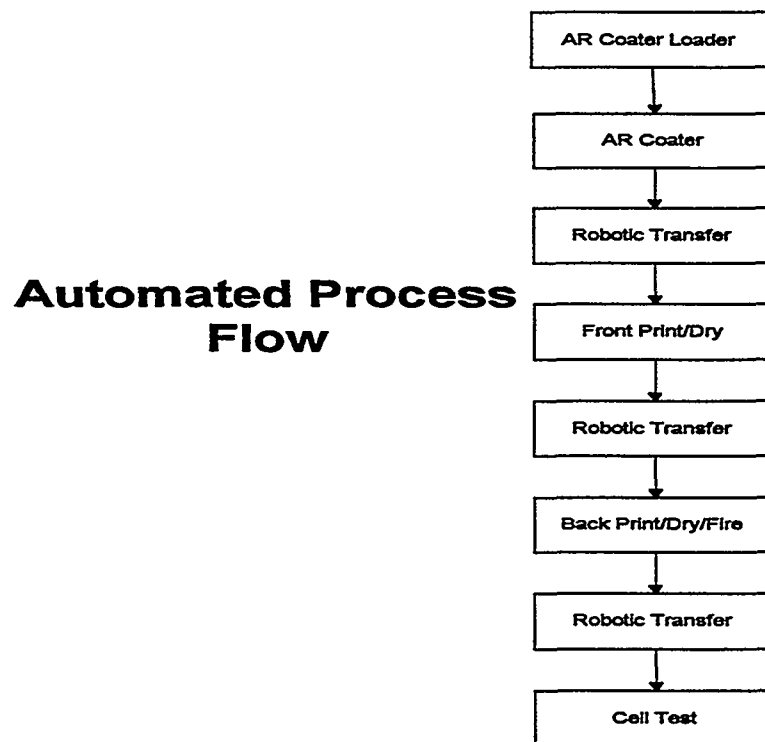


Figure 2-4. Automated Cell processing flow

2.5 Cell Processing Mechanical Yield:

Yield in the cell line as mentioned above in the wafering and crystal growing processes, is a large driver in the costs of manufacturing photovoltaics. The cell yield is important as it incorporates the cumulative costs of ingot growth, wafer slicing and cleaning and the cell process itself. Over the reporting period, cell mechanical yields have improved by over 15%. This is attributed to better handling by robotics, more attention to manual handling steps, and better understanding and training of operations personnel.

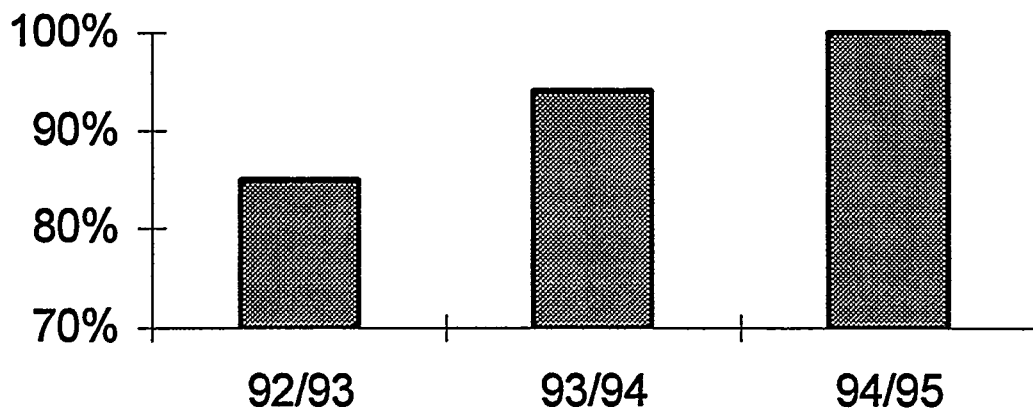


Fig. 2-5. Cell Yield Improvement

SECTION 3.0

MODULE FABRICATION AND ENVIRONMENTAL, SAFETY AND HEALTH ISSUES

3.1 Module Development:

A majority of the module finishing costs in photovoltaics are in the materials and labor used for fabricating the modules. The requirement of reliability has driven the industry to standardize the laminate design to include glass, EVA, and various back sheet materials which provide an electrically insulating, environmentally resistant package. In working through the opportunity to reduce costs in the module design, three things became apparent during this phase of the contract: the module size has a significant impact on the dollar per watt material cost, the laminate construction is the significant contributor to the labor component of the costs, and the framing and junction box are major material contributors. During this contract, all three have been addressed.

The first of these improvements showed the use of anti-reflective glass etching to decrease the amount of reflected light on a module surface. Greater than a 1 Watt improvement in electrical power was seen on M55 style modules (reference Figures 3-1. and 3-2 respectively). This gain is shown in Figure 3-3. with varying the degree of etch. Although this proved to be a significant electrical performance boost at a low cost, the commercial availability of this glass is quite limited, and use of this material in high volume manufacturing is not feasible.

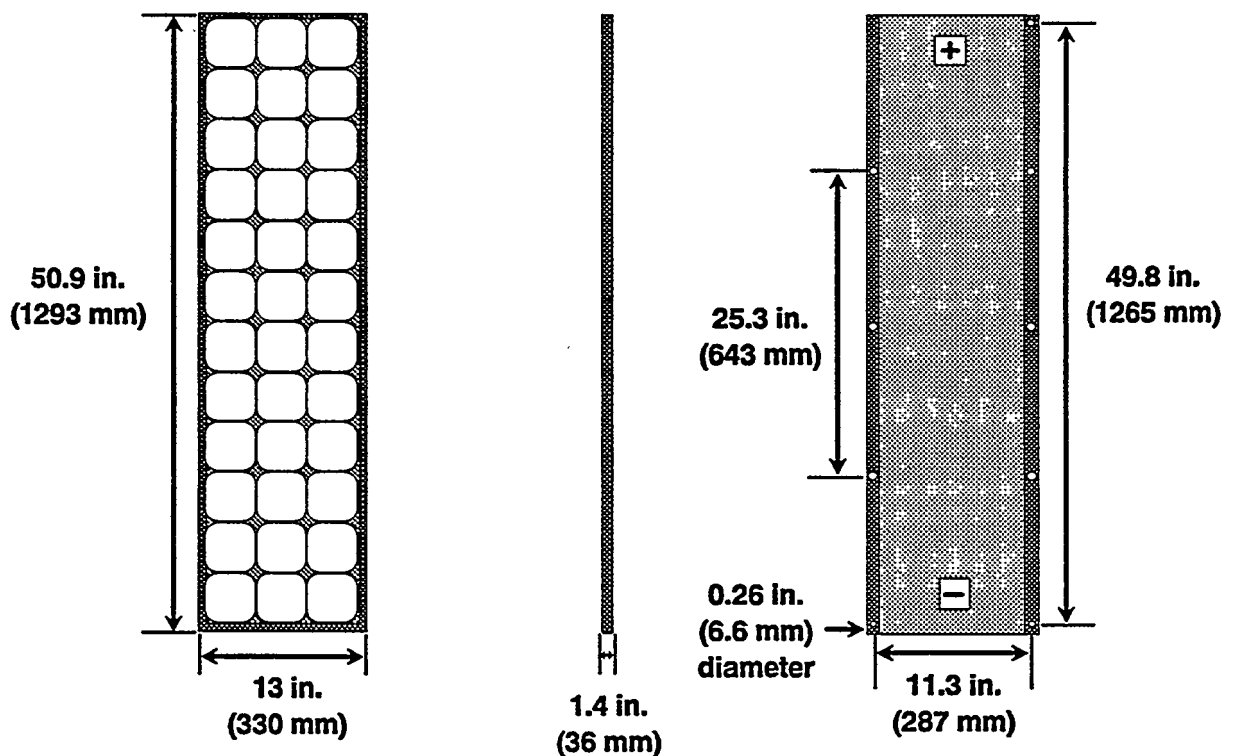


Fig. 3-1. M55 Module Design

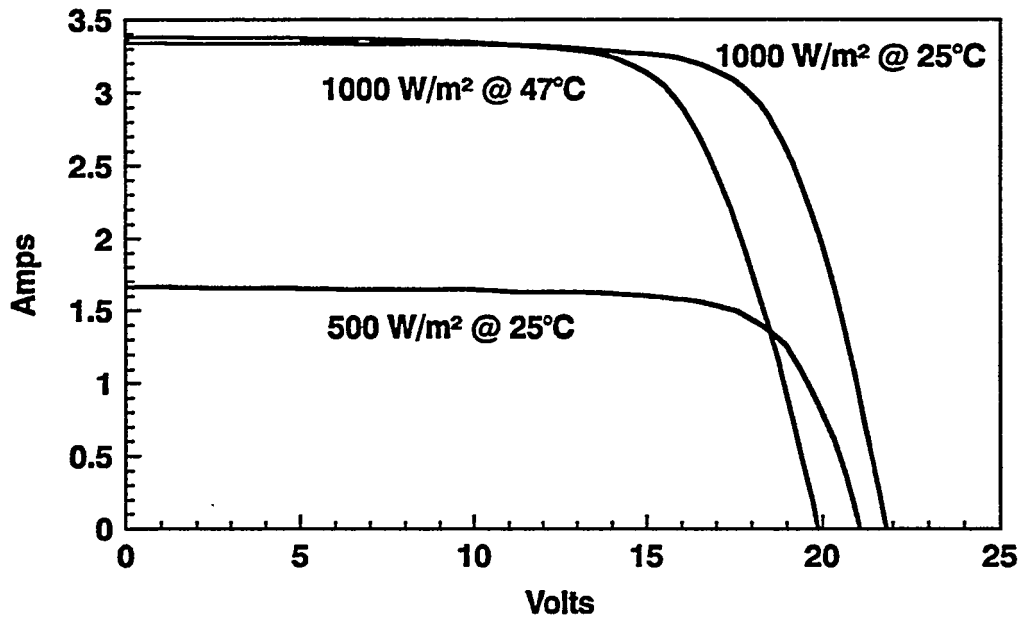


Fig. 3-2. M55 Electrical Characteristics

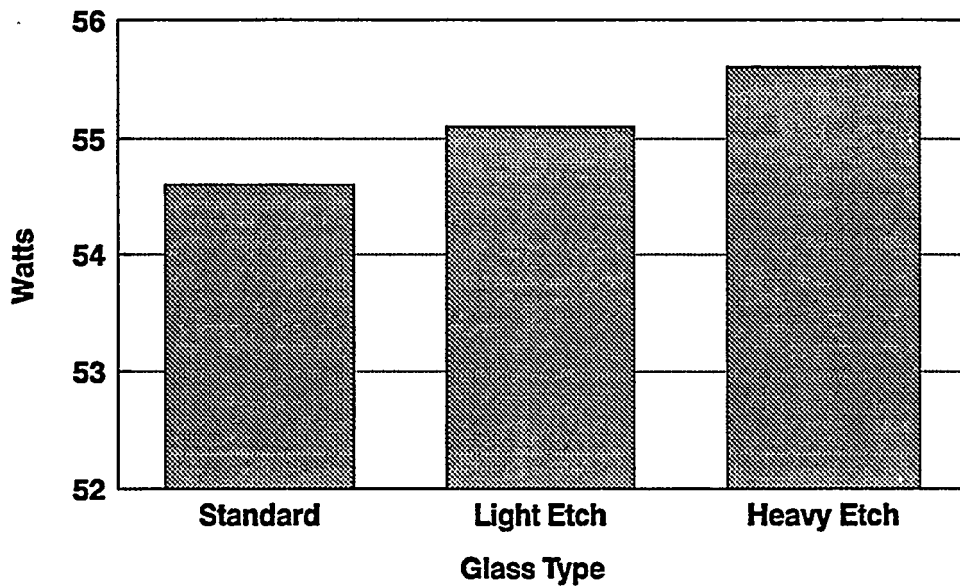


Fig. 3-3. Anti-Reflective Glass Performance Improvement

A second item which showed significant benefit is the use of a "whiter" Tedlar™ backsheet which gave an overall 0.5 Watt gain in electrical performance on an M55 module. The use of "whiter" Tedlar™ has been implemented in full scale production.

3.2 75 Watt Module Design:

To address the larger module and its affect on reducing the dollar per watt, a larger ingot which could be grown easily in the facility was chosen. The starting design assumptions were to maximize the amount of power in a given module unit. Coupling this assumption with the ingot design, gave a cell area which is 35% larger than the 4.05" square cell. This cell power is further enhanced by the white area of the laminate using larger spacing of the cells. Modules made from thirty six cells in series produce 75 Watts in this new module design. The IV curve for the 75 Watt module is shown in Figure 3.4.

Other significant design changes considered were the framing technique and electrical termination used. Two modules were designed, one with the standard aluminum frame and a large junction box, and one with a plastic frame and a two conductor cable assembly. In the final cost summary, the two module techniques were similar in dollar per watt, where the savings of the plastic frame were offset by the labor and expense of the cable assembly technique. The significant cost reduction is mainly due to the larger amount of watts (75 v. 53) being framed and terminated. The two 75 Watt module designs are shown in Figure 3.5.

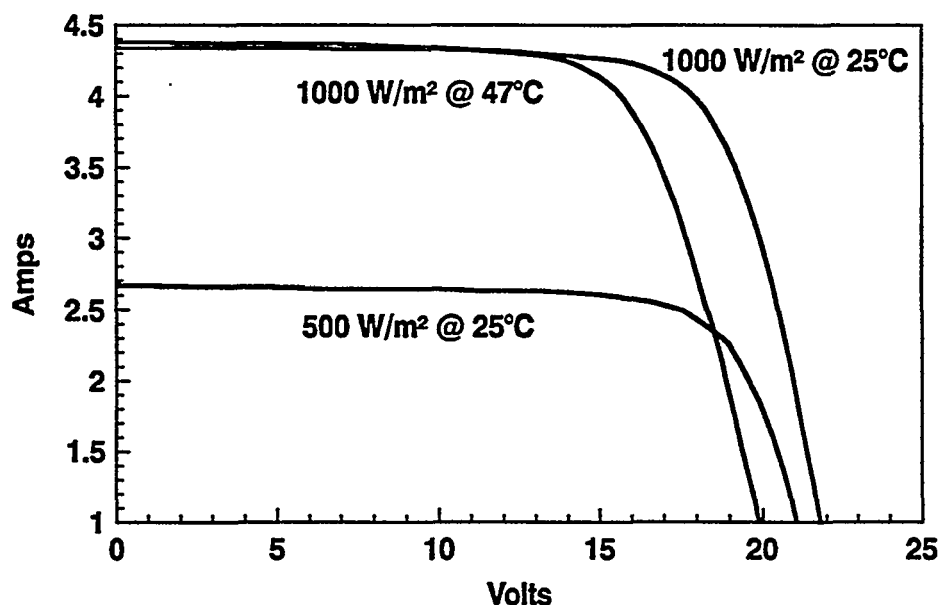


Fig. 3-4. I-V characteristics for a 75 Watt module.

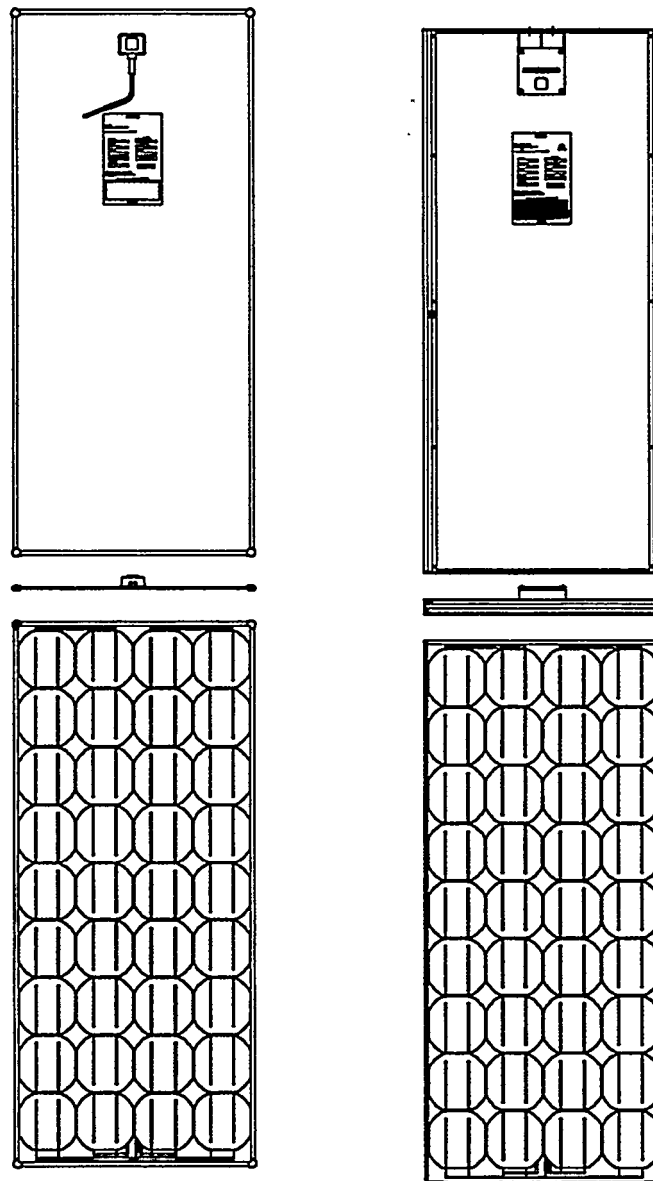


Fig. 3-5. 75 Watt module designs.

3.3 New Junction Box:

A new junction box has been designed which combines the benefit of the wire termination and the large junction box. A cost reduction benefit of over 2% is expected in production. The new junction box allows for wire connections and conduit type fitting connections. The installation of this new design on the module during manufacturing has also been considered, with an open area for laminate ribbon to feed through for electrical connection and larger area contact for gluing to the module back surface. The new design is shown in Figure 3.6. This junction box has been approved by Underwriters Laboratory, and is planned to be implemented full scale in the production line.

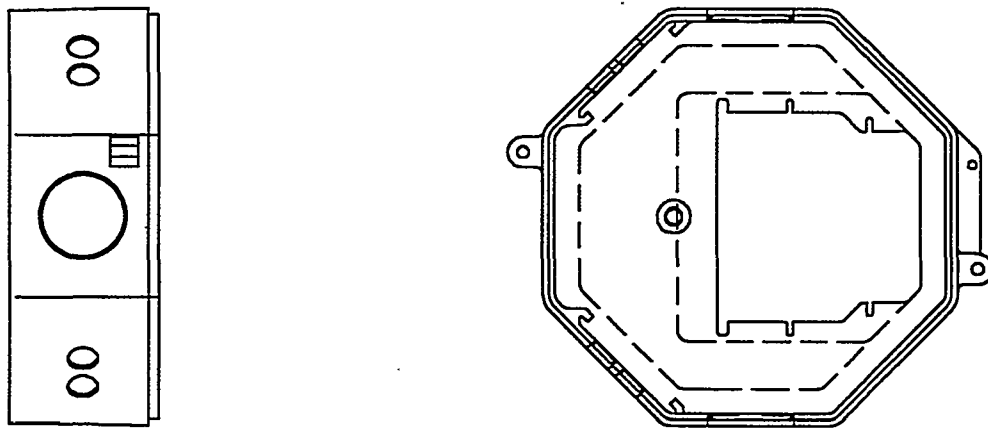


Fig. 3-6. New j-box design

3.4 Semi-Automated Assembly Line:

A design for a semi-automated assembly line for 75 Watt laminate manufacturing has been finished during this phase. The design is a flexible material movement system which relies on fixtures which travel along a track system. The operators of the system place cells on the fixtures which move down the line for final solder connections and laminate lay-up. This design will allow for a 30% reduction in the amount of labor required for assembling 75 Watt laminates. An additional requirement of ergonomic comfort has been included in this design. The system layout is shown in Fig. 3-7.

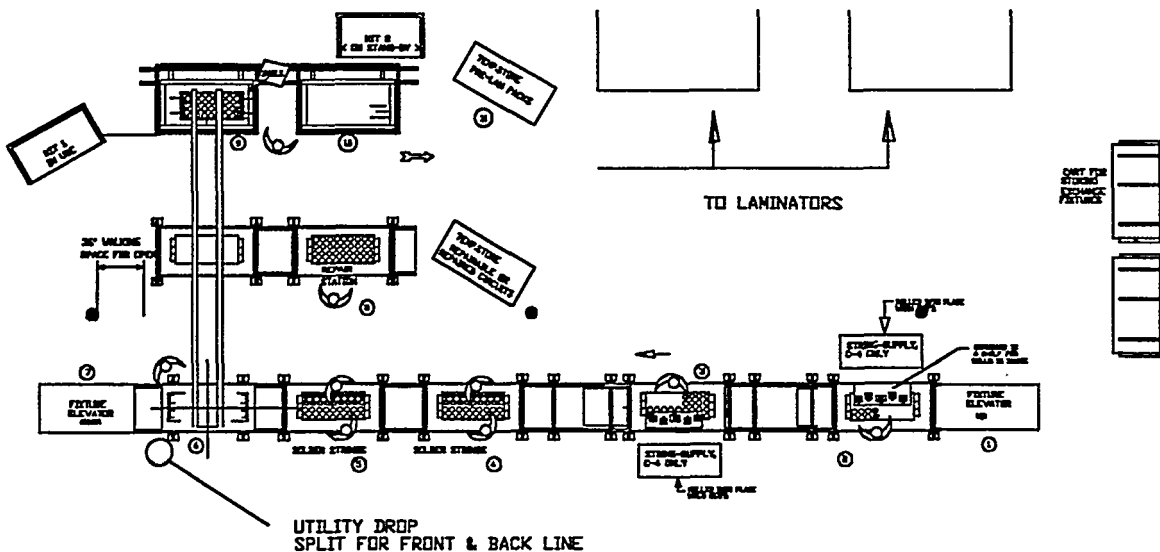


Fig. 3-7. Layout of semi-automated assembly line.

3.5 Module Assembly Yield:

A significant finding during the program has been that the yields in the soldering process are the drivers to high yield in the module making process. A primary process control parameter in soldering is the edge condition of the cells being soldered. Figure 3-8. shows the relationship of yield to chipped cells, which results in a lowering of process yield by over 3%. Good quality cells are an essential requirement to high module yield and the improvements noted in section 2 of this report have contributed to higher module yields. Overall, mechanical yields in the module area of manufacturing have been improved by 20% under this contract, as shown in Figure 3-9.

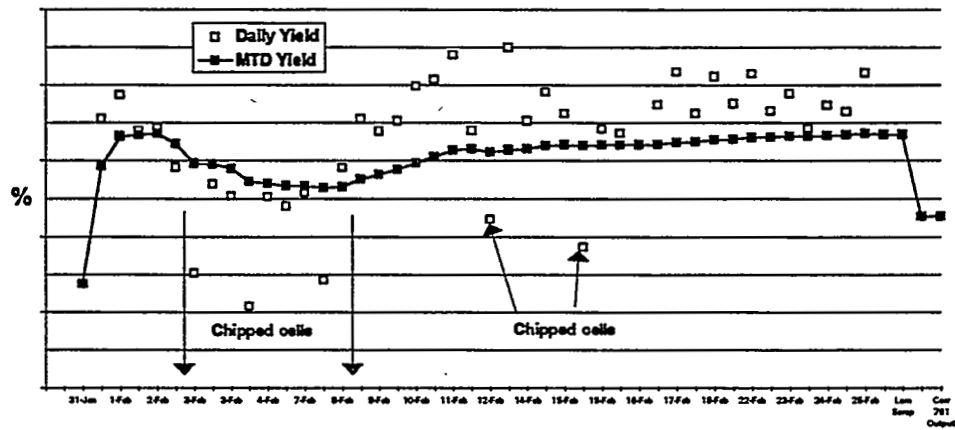


Fig. 3-8. Solder Process Yield

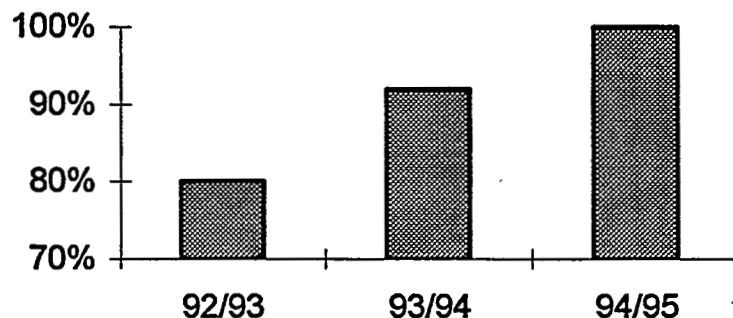


Fig. 3-9. Module Yield Improvement

3.6 Environmental, Safety and Health Issues

In the area of Environmental, Safety and Health Issues task, the focus during this contract has been on the elimination of chlorofluorocarbon (CFC) usage in the manufacturing facility. The project had three phases:

- The reduction of CFC usage in manufacturing
- Evaluation of alternative solder paste materials which do not require CFC cleaning
- The removal of CFCs and the implementation of the alternative solder paste materials

The CFC usage reduction program evaluated both using CFCs more efficiently and alternatives to CFCs for cleaning. Work began on assessing water soluble flux options and various low solids fluxes for soldering. In conjunction, several opportunities for reduction were identified and implemented:

- Additional tank coverage to reduce the amount of evaporation from the ultrasonic baths used for defluxing of solder points.
- Colder chilling water to help condense and trap more liquid for re-use.
- Cleaning of fan blades, screens and heat sinks to help maintain the maximum heat exchange rate for condensation of vapors.
- Re-plumbing of chill water lines for additional cooling capacity.

These modifications to the ultrasonic baths were implemented and produced a reduction in CFC usage of approximately 60%.

The first round of testing for alternative solder paste materials involved water soluble solder flux, which looked promising for replacing the flux currently used in production. Subsequent qualification of the modules in Block V tests failed in less than five humidity-freeze cycles. It appears that the water rinse of the cells retained moisture during the lamination sequence. The modules appeared cloudy and showed a tendency to delaminate the EVA bond after a short humidity-freeze exposure. From this information, water soluble fluxes were abandoned as an appropriate substitute for CFC defluxing.

The next focus was on low solids fluxes that could be left on the substrate after soldering. An assortment of candidate solders were tested. Modules were made from each solder to first evaluate its compatibility with the in-house soldering equipment (semi-automatic and manual), followed by full environmental testing. The flow chart in Figure 3-10. shows the series of experiments:

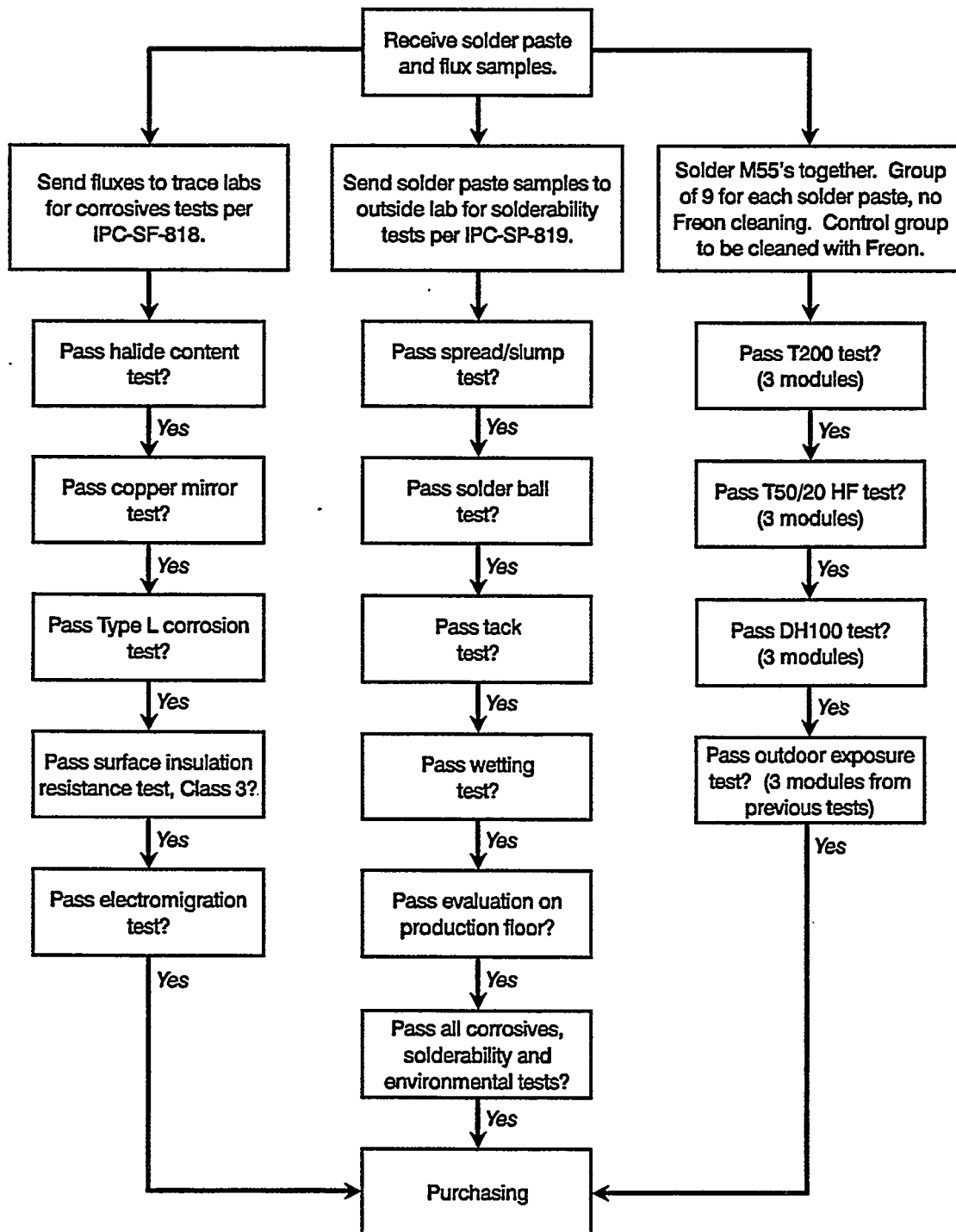


Fig. 3-10. Flowchart showing experiments conducted.

Of solder pastes evaluated, one proved to be acceptable, passing all required characteristics. The following table indicates which pastes were evaluated and their results:

Table 3-1. Solder Paste Evaluation

Manufacturer	Mfg #	Corrosive Level of Flux	Block V Test
Heraeus Cermalloy	SC3610S-1	Pass	Fail
Alpha Metals	LR701	Pass	Fail
Kester	R-244	Pass	Fail
ESP	6-Sn62-500-A	Pass	Pass
Alpha Metals	RMA 341	Fail	Fail
Heraeus Cermalloy	SC3300S	Pass	Fail
AIM	LR5	Fail	Not done
IEM Fusion	NCR-D-7C-3	Fail	Not Done
Dupont	VLR0620	Fail	Not Done
Heraeus Cermalloy	Flux#SF-33-2	Pass	Fail

After selection of the paste, implementation in manufacturing started. This included:

- Modifications to the solder paste application system (hardware and software)
- Modifications to the soldering lamp temperature profile and soldering time
- Installation of the new "no-clean solder paste" with continued CFC cleaning to verify application technique and soldering criteria acceptability/process debug
- Documentation of new solder paste specifications, process procedures, bills of materials, and equipment modifications
- Removal of ultra-sonic CFC defluxing equipment
- Training of manufacturing personnel
- Re-evaluation of random modules produced by manufacturing through Block 5 test

The complete removal of CFCs from manufacturing occurred during May 1993. We continue to evaluate the equipment and solder paste performance. At the present time work also continues on the issue of alternative solder flux cleaning methods, since there is "some" flux remaining on the cell. Additionally, lower viscosity pastes are being evaluated to improve the "dispensibility" of the material.

One concern in implementing this new paste was the long term affect on module reliability and adhesion of the cell surface to EVA in the presence of this flux. A study was conducted by Springborn Laboratories with SSI to evaluate and quantify this effect [2]. Figure 3-11. shows the effect of adhesion values of EVA to the cell surface v. concentration of flux present. As can be seen by the graph, the adhesion drops in the presence of flux, and has to be controlled to a minimum value present. This is a strong quality control point in the manufacturing line.

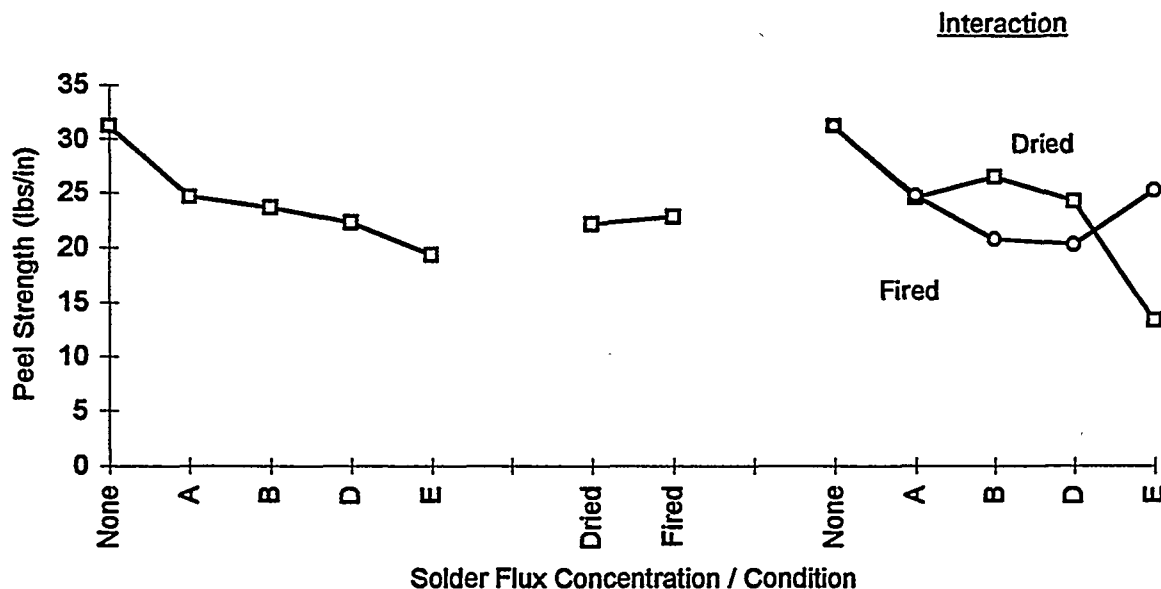


Fig. 3-11. Adhesion v. Flux concentration

Caustic Waste and Fluoride Waste Reduction

The second task in the Safety, Health and Environmental area is the significant reduction of the caustic waste volumes and the removal of Fluoride from the waste stream. Several vendors were investigated with two primary vendors proposing methods for production use.

Figures 3-12. and 3-13. show the proposed methods for caustic waste reduction and fluoride waste reduction respectively. SSI is presently evaluating the proposals from both engineering groups.

The treatment of the waste requires several difficult environmental permits, and there have emerged opportunities to remove our waste through companies which use the caustic to neutralize acidic waste streams. This has been chosen as the business approach to the problem with encouraging results as discussed below.

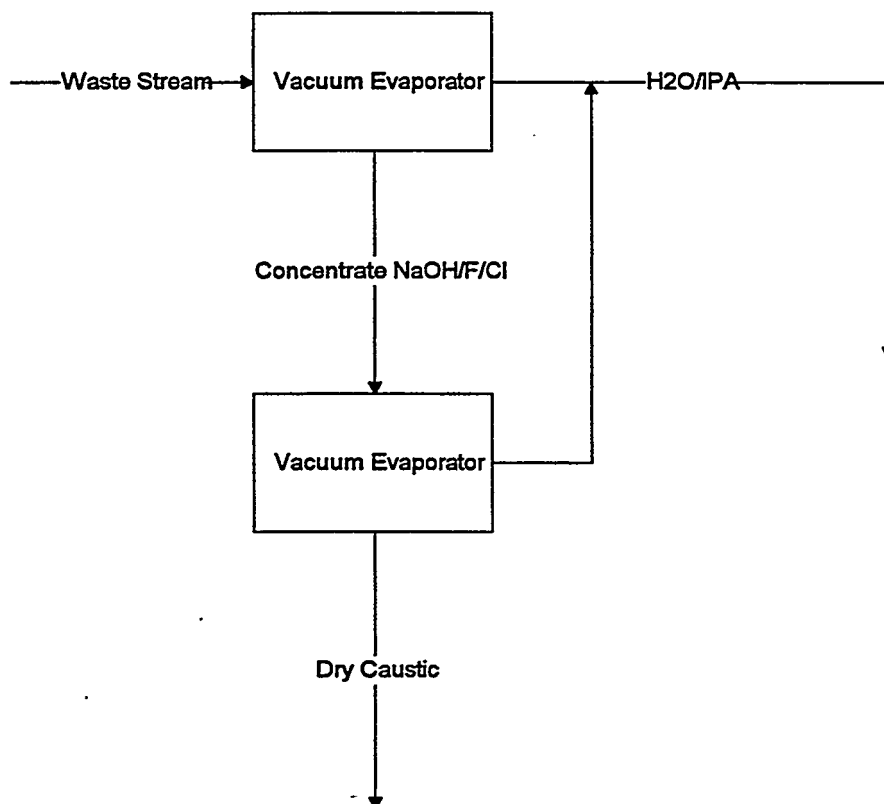
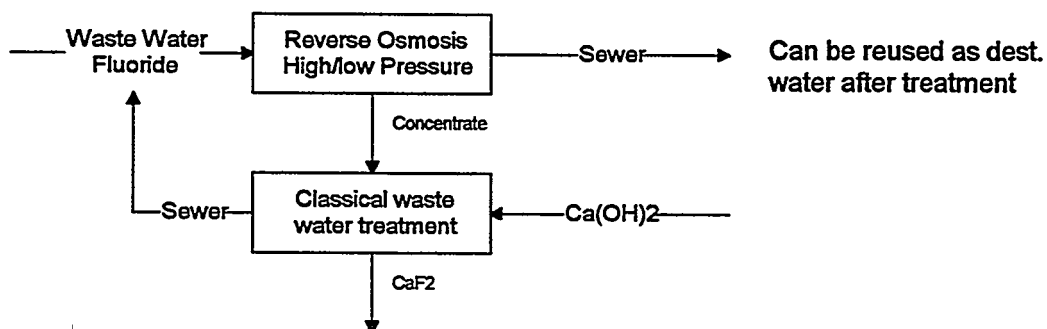
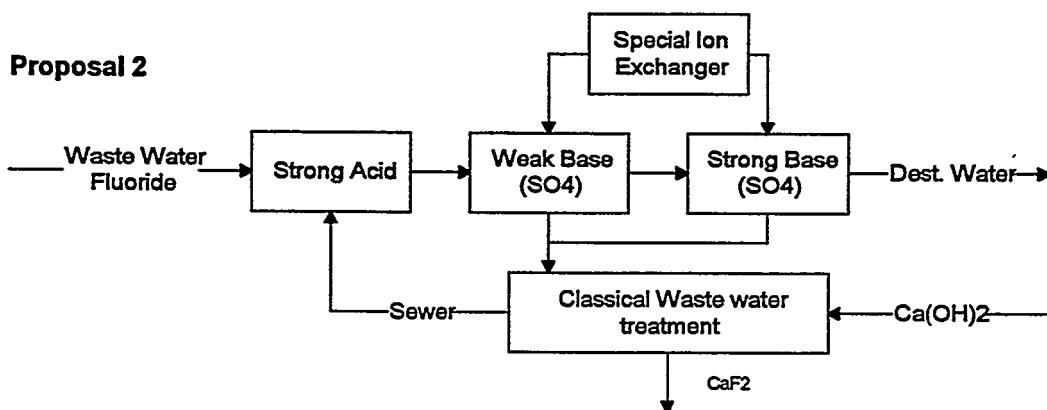


Fig. 3-12. Proposed Caustic Waste Reduction Process

Proposal 1



Proposal 2



Proposal 3

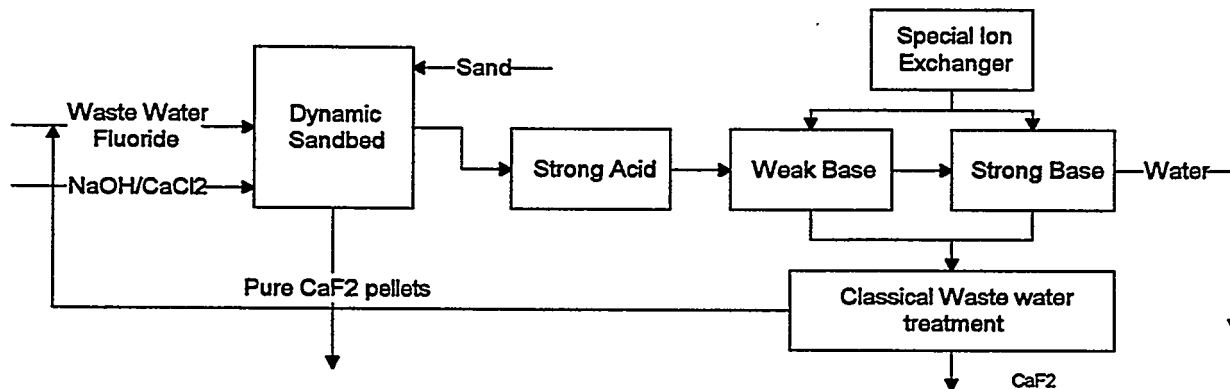


Fig. 3-13. Proposed Fluoride Waste Reduction Processes

In parallel, a focus on reducing caustic waste generated and its associated cost has been attacked using two methods. The first method is the reduction of waste created per cell processed. This has been accomplished mainly with the use of wire sawn wafers which require less etching to remove saw damage, and the extension of the life of the etching baths. This reduction in caustic waste per wafer is over 20% for the reporting period of this contract. The cost of waste per cell has dropped by almost 65% in the last two years. The volume and cost reduction are shown in Figure 3-14.

All Safety, Health and Environmental deliverables were met under this contract.

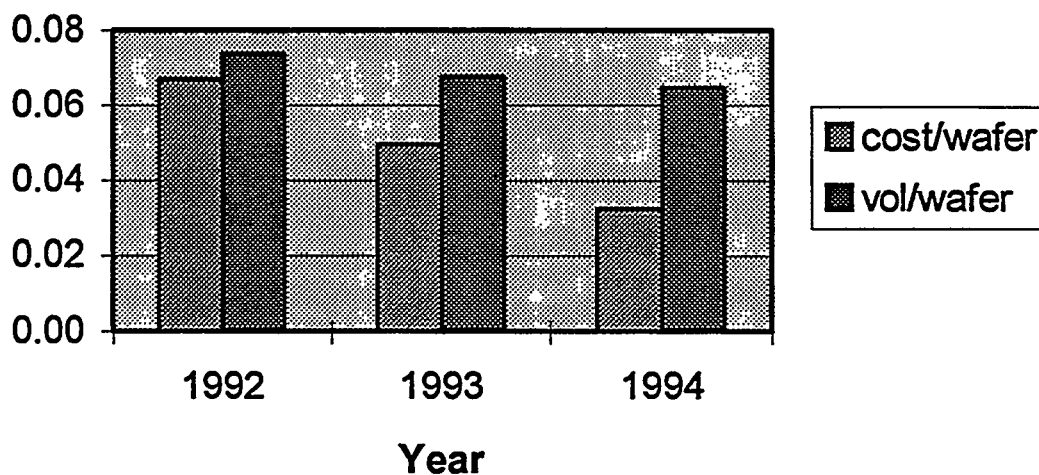


Figure 3-14. Caustic Waste Reduction in volume and cost

REFERENCES

- [1]K.L. Pauls et al., "The Effect of Dislocations on the Performance of Silicon Solar Cells", *23rd IEEE Specialist Conference*, 1993
- [2]T.L. Jester et al., "A More Fundamental Examination of Factors Governing PV Module Environmental Stability", *IEEE First World Conference on Photovoltaic Energy Conversion*, 1994

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 1995	3. REPORT TYPE AND DATES COVERED Final Subcontract Report, 1 April 1992 - 31 May 1995	
4. TITLE AND SUBTITLE PV Cz Silicon Manufacturing Technology Improvements		5. FUNDING NUMBERS C: ZM-2-11040-1 TA: PV550101	
6. AUTHOR(S) T. Jester			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Siemens Solar Industries 4650 Adohr Lane Camarillo, CA 93012		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393		10. SPONSORING/MONITORING AGENCY REPORT NUMBER TP-411-20016 DE95013125	
11. SUPPLEMENTARY NOTES NREL Technical Monitor: R. Mitchell			
12a. DISTRIBUTION/AVAILABILITY STATEMENT		12b. DISTRIBUTION CODE UC-1280	
13. ABSTRACT (Maximum 200 words) This report describes work performed by Siemens Solar Industries (SSI) under a 3-year, three-phase, cost-shared contract to demonstrate significant cost reductions and improvements in manufacturing technology. The work focused on near-term projects for implementation in the SSI Czochralski (Cz) manufacturing facility in Camarillo, California. The work was undertaken to increase the commercial viability and volume of photovoltaic manufacturing by evaluating the most significant cost categories and then lowering the cost of each item through experimentation, materials refinement, and better industrial engineering.			
14. SUBJECT TERMS silicon ; Czochralski ; manufacturing ; photovoltaics ; solar cells		15. NUMBER OF PAGES 43	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL